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Advances in Δm_d measurements

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We report the current status of Δm_d measurements at B-factories. The most recent world average is $\Delta m_d = 0.502 \pm 0.007$ ps^{-1} (1.4% accuracy). An estimate of the errors for 500 fb^{-1} data is also given.

1 Introduction

In the Standard Model, B^0-$\overline{B}^0$ oscillations occur through second-order weak interactions, mainly through internal loops containing virtual t quarks. The mixing parameter Δm_d, the mass difference between the two mass eigenstates, is thus related to the V_{tb} and V_{td} CKM matrix elements. The measurement of Δm_d can therefore in principle provide a means to extract $|V_{td}|$. In addition, Δm_d plays a role in the parameterization of the CP asymmetries in the B^0 system: a precise measurement of Δm_d is also needed for CP violation measurements (see [1,2]).

In this article, we present different measurements of Δm_d from the time distributions of opposite-flavor (OF – $B^0\overline{B}^0$) and same-flavor (SF – B^0B^0, $\overline{B}^0\overline{B}^0$) neutral B decays at the $\Upsilon(4S)$ resonance. The theoretical time-dependent probabilities for observing OF and SF states are given by:

$$\begin{aligned} \mathcal{P}^{\mathrm{OF}}(\Delta t) &= \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 + \cos(\Delta m_d\, \Delta t)] \\ \mathcal{P}^{\mathrm{SF}}(\Delta t) &= \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 - \cos(\Delta m_d\, \Delta t)] \end{aligned} \tag{1}$$

where τ_{B^0} is the B^0 lifetime and Δt is the proper time difference between the two B meson decays. This assumes CP and CPT conservation in the mixing, as well as negligible $\Delta\Gamma$ (decay width difference between the two B meson mass eigenstates).

The analyses presented here were performed on data collected with the BaBar and the Belle detectors [3]. A 9 GeV (resp. 8 GeV) electron beam and a 3.1 GeV (resp. 3.5 GeV) positron beam are collided in the PEPII (resp. KEKB) storage ring, resulting in a Lorentz boost of the center-of-mass of $\beta\gamma = 0.55$ (resp. 0.425) with respect to the laboratory frame. Since B mesons are nearly at rest in the $\Upsilon(4S)$ frame, the proper time difference Δt is approximated by $\Delta z/\beta\gamma c$, Δz being the (signed) distance between the decay vertices of the two B mesons along the beam axis. The flavor of the B mesons is determined using flavor-specific decays.

2 Dilepton measurement

In this analysis [4,5], semi-leptonic decays $B \to X^- l^+ \nu_l$ from both B mesons are used to tag the B flavor with the sign of the lepton. Two fast leptons are searched for. The decay vertex position of the B meson is determined from the interception of the lepton track with the profile of the interaction point. Because of the large semi-leptonic branching fraction, this analysis offers the largest statistics. However, the purity of the signal is affected by the background coming from charged B mesons.

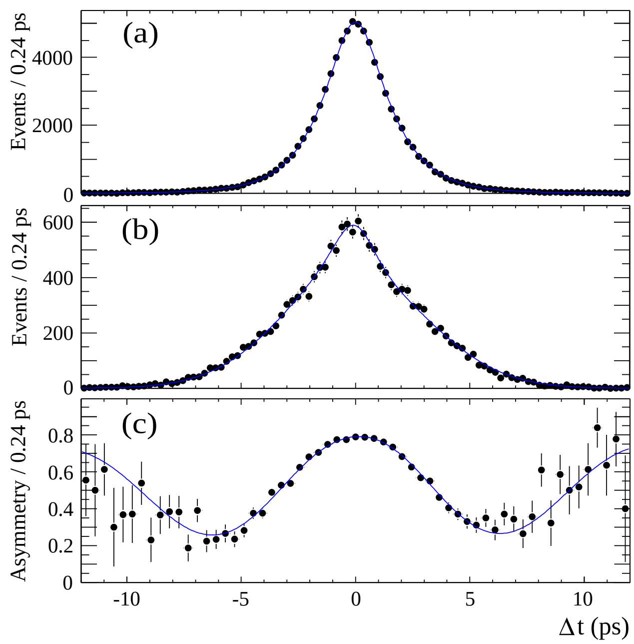

Figure 1. Result of the fit for the dilepton measurement by BaBar on (a) OF and (b) SF events, and the corresponding mixing asymmetry $(N_{\mathrm{OF}} - N_{\mathrm{SF}})/(N_{\mathrm{OF}} + N_{\mathrm{SF}})$.

This selection has been applied on 20 fb^{-1} on-resonance data from BaBar (about 22 million B meson pairs), yielding $\Delta m_d = 0.493 \pm 0.012 \pm 0.009\,\mathrm{ps}^{-1}$ (see Fig. 1, also showing the mixing asymmetry $(N_{\mathrm{OF}} - N_{\mathrm{SF}})/(N_{\mathrm{OF}} + N_{\mathrm{SF}})$). Belle obtains $\Delta m_d = 0.503 \pm 0.008 \pm 0.010$ ps^{-1} from 29.4 fb^{-1} on-resonance data (see Fig. 2). At present, the latter is the

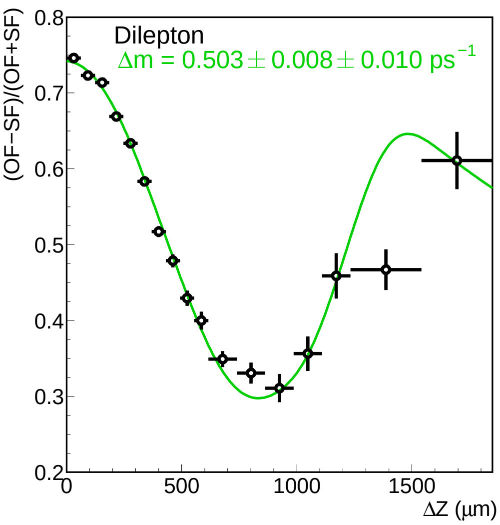

Figure 2. Mixing asymmetry fitted by Belle on the dilepton Δz distributions.

most precise single measurement of Δm_d (with an accuracy of about 2.5%).

3 $D^* \pi$ partial reconstruction

Belle uses another partial reconstruction method [6] to extract Δm_d from $B^0 \to D^{*-}\pi_f^+$ decays. The D^{*-} information is extrapolated from the soft pion of $D^{*-} \to \overline{D}^0\pi_s^-$, and then combined with the fast pion π_f^+ and the beam information to reconstruct the B meson. The flavor is given by the charge of the fast pion. The other side is tagged by simply looking for a fast lepton. 31 fb^{-1} on-resonance data was used in this measurement.

Contributions of various backgrounds can be estimated from the D^0 "missing mass" (see Fig. 3). A simultaneous unbinned maximum likelihood fit to OF and SF events yields: $\Delta m_d = 0.509 \pm 0.017 \pm 0.020\ \text{ps}^{-1}$.

4 $D^* \ell \nu$ full reconstruction

This method [7,8] fully reconstructs $B^0 \to D^{*-}\ell^+\nu$, with $D^{*-} \to \overline{D}^0\pi^-$ and $\overline{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, or $K^+\pi^-\pi^+\pi^-$ (BaBar also reconstructs $K_s\pi^+\pi^-$). The flavor of the other B meson is tagged using the same algorithms as in Ref. [1,2] (a neural network for BaBar, a multidimensional likelihood for Belle).

The cosine of the angle between the reconstructed $D^*\ell$ system and the B meson momenta in the $\Upsilon(4S)$ frame is used to separate the signal from various backgrounds (D^{**}, fake D^*, random $D^*\ell$ and continuum). An unbinned maximum likelihood fit is then performed on the Δz distributions. The results of the fit by BaBar, shown on Fig. 4, yields

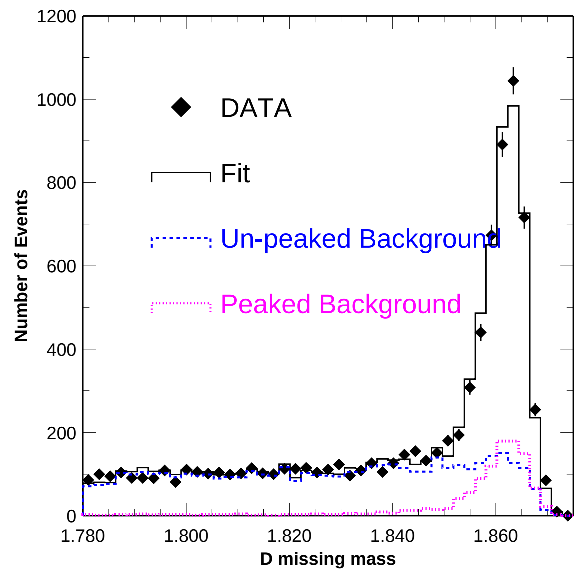

Figure 3. The D^0 "missing mass" fitted with Monte-Carlo data for the $D^*\pi$ measurement (Belle).

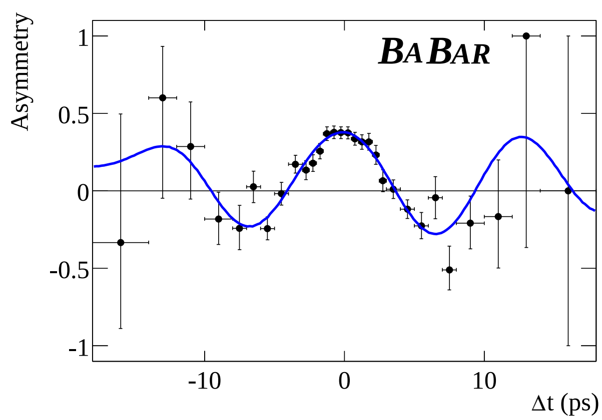

Figure 4. Mixing asymmetry showing the data points and the overlaid fit to Δz distributions from the $D^*\ell\nu$ analysis (BaBar).

$\Delta m_d = 0.492 \pm 0.018 \pm 0.013\ \text{ps}^{-1}$ (from 20 fb^{-1}). Belle obtains $\Delta m_d = 0.494 \pm 0.012 \pm 0.015\ \text{ps}^{-1}$ from 29 fb^{-1}.

5 Hadronic modes

The exclusive reconstruction of B mesons decaying into flavor specific hadronic states has also been used to measure Δm_d [9,10]. Neutral B mesons are reconstructed in the decay modes $D^{(*)+}\pi^-$ and $D^{(*)+}\rho^-$ (and also $D^{(*)+}a_1^-$ by BaBar), with D^{*+} decaying into $D^0\pi^+$ and D^0 decaying into $K^-\pi^+$, $K^-\pi^+\pi^0$ or $K^-\pi^+\pi^-\pi^+$ (or also $K_s\pi^+$ in BaBar's case). The ρ^- and a_1^- are formed of $\pi^0\pi^-$ and $\pi^-\pi^+\pi^-$, respectively. Finally, BaBar also includes B^0 decaying into $J/\psi K^{*0}$. The other side is tagged using a flavour tagging algorithm, as in the previous analysis (see [1,2]).

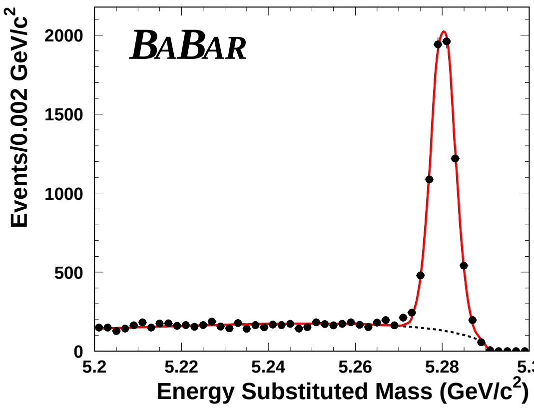

Figure 5. Fit of background (dashed) and signal (solid) contributions to the “energy-substituted mass” (BaBar).

The signal region is defined by constraints on $\Delta E = E^*_B - E^*_{\rm beam}$ and $M_{\rm bc} = \sqrt{E^{*\,2}_{\rm beam} - p^{*\,2}_B}$, where E^*_B and p^*_B are the center-of-mass energy and momentum of the fully reconstructed B candidate, and $E^*_{\rm beam}$ is the center-of-mass energy of the beam. The background contributions can be fitted from $M_{\rm bc}$, the “energy-substituted mass”, as shown on Fig. 5.

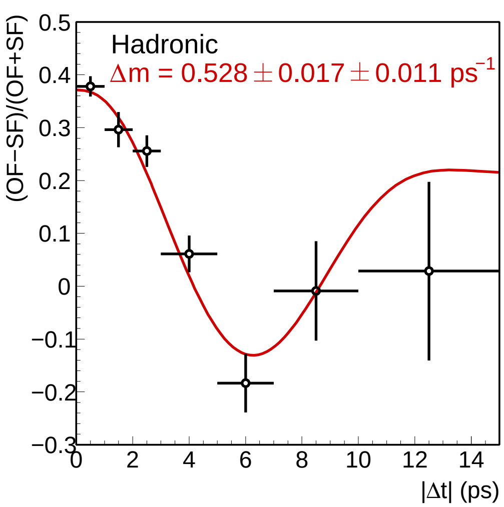

Figure 6. Mixing asymmetry and result of the fit to hadronic modes (Belle).

BaBar performs an unbinned likelihood fit including resolution parameters on 30 fb^{-1} on-resonance data and finds $\Delta m_d = 0.516 \pm 0.016 \pm 0.010$. Belle uses the resolution function used for lifetime measurements [11] and obtains $\Delta m_d = 0.528 \pm 0.017 \pm 0.011$ ps^{-1} from 29 fb^{-1} on-resonance data (see Fig. 6).

6 Summary and prospects

Fig. 7 shows the most up-to-date summary of the results, as selected for the 2003 issue of the PDG review. The world average is: $\Delta m_d = 0.502 \pm 0.007$ ps^{-1} [12] (including statistical and systematical errors), with an accuracy of 1.4%.

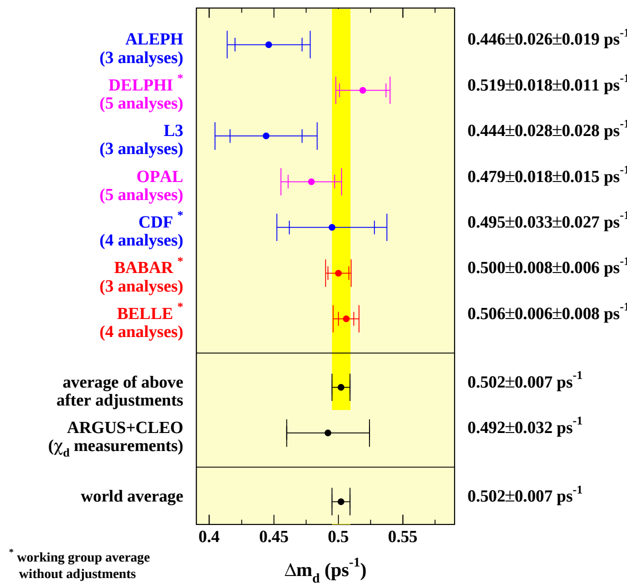

Figure 7. Summary of Δm_d measurements and current world average.

Within 3 years, BaBar and Belle will have collected 500 fb^{-1} each (about 15 times more than what was used here). An extrapolation of the systematic errors for each individual measurement has been made in order to estimate the accuracy on Δm_d that could be reached. Improvement of the current limiting systematic errors are evaluated from: a better precision on the B lifetime, a larger amount of Monte-Carlo statistics, an accurate measurement of some branching fractions (e.g. $B \to D^{**}\,\ell\,\nu$). In addition, resolution parameters are expected to be better extracted from data. The average value is then computed in the same way as for the world average, with the central value fixed to the present average. A total error of 0.0023 ps^{-1} is found, which corresponds to 0.5% of 0.502 ps^{-1}.

These extrapolations do not take into account possible improvements of the existing analyses. On the other hand, the evolution of systematic errors is hard to predict. This 0.5% accuracy should therefore be treated carefully.

7 Conclusion

A number of measurements of Δm_d have been performed by the BaBar and Belle collaborations. These efforts have lead to a world average of $\Delta m_d = 0.502 \pm 0.007$ ps^{-1}. The

error takes into account statistical and systematical correlations between the measurements. The current accuracy on Δm_d is currently 1.4%, and is expected to reduce to about half a percent within a few years.

In the future, Δm_s will be measured with high precision. The error on Δm_d may then become a limiting factor on the determination of related CKM matrix parameters (see discussion in [13], chapters 4 and 5). In the meanwhile, as the accuracy on Δm_d is approaching the percent level, efforts are moving to more fundamental tests of underlying assumptions. Limits on CPT violating parameters have been set [5], and measurements of $\Delta\Gamma$ have started [14].

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